FROM THE CHIEF SCIENTIST'S DESK

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The current status of Magnetic Materials Science and Engineering at the NHMFL is discussed in relation to future developments in these areas. NHMFL Chief Technology Officer Hans Schneider-Muntau discusses various opportunities for new projects.

Materials Research for Advanced Magnets

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The world records achieved at the NHMFL—the 25 T high-temperature superconductor (HTS) insert, the 33 T resistive magnets, and the 45 T hybrid magnet—are the result of a visionary magnet science and technology program from the beginning and continuous development work over many years. The 25 HTS insert is the consequence of many years' efforts, and a fruitful and trustful cooperation with industry. The success of the resistive and Hybrid magnet program would not have been possible without the invention of the Florida-Bitter magnet by one of the authors. The achievements with our pulse magnets put us on equal footing with other laboratories. The 900 MHz system will be the largest high-field magnet ever built. These accomplishments conclude the build-up phase as suggested by the Seitz-Richardson report.

It is a relevant question to ask what should be the next step. A common feature of all our magnets is that, after having developed a detailed understanding of the physics of magnets, and consequently optimized magnet design, we find our limitations in the deficiencies of the materials we have to use. If we want to maintain our leadership, we now have to break new grounds in materials research for magnets. Better conductors, insulators and reinforcement materials would not only help to achieve higher fields but would also improve the quality of the magnets, such as higher longevity, and better efficiency. In the following, we propose material development activities that are crucial for further progress in magnetic fields. We will deal with the major constraints in HTS, resistive, and pulse magnets through the limitations imposed by the mechanical properties of the conductors and reinforcement materials. We then propose a variety of approaches to establish a tailored materials development program.

Material Limitations in High-Field Magnet Designs

High-Temperature Superconductor Magnets

During the development of the 5 T HTS insert, major design challenges had to be overcome, such as space limitation because of the inner diameter of the outer magnet, high Lorentz forces due to the background field, magnetic interaction between the two coils, the anisotropy of the conductor, and other issues.[1] The step to higher fields with HTS inserts will need better conductors and reinforcement. Similar to Nb_3Sn, HTS conductors have a critical strain value beyond which strain degradation occurs. For most of the alloy-clad Ag conductors a strain tolerance of 0.4 to 0.5% has been demonstrated. The strain on the conductor can be reduced by adding reinforcement that shares part of the Lorentz forces. The Young's modulus of the reinforcement determines the load distribution between the conductor and the reinforcement. The presence of the reinforcement dilutes the current density of the winding, and a reduced average overall current density results, limiting the achievable field. Figure 1 shows that an increase of the current density within the superconductor only translates into a modest increase in average current density of the reinforced conductor, and levels off for higher current densities.

It results that future efforts have to focus on conductors with higher strain tolerance, and better reinforcement materials. Multiphase alloys, such as MP35N, with an ultimate tensile strength (UTS) of 2.5 GPa and a Young's modulus of 240 MPa at 77 K,[3] or composites of organic fibers, such as Zylon, with a UTS of up to 5 GPa and Young's modulus of 180 GPa,[4] might be materials of choice for the generation of even higher fields with HTS. Organic fibers have the additional advantage of being good insulators and not magnetic. Differences in thermal contraction between conductor and reinforcement would have to be investigated. The method developed at the NHMFL to coat the reinforcement tape

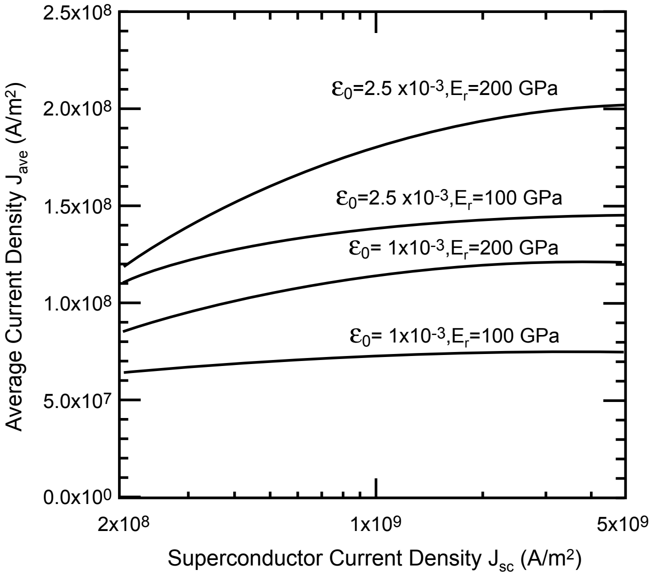

Figure 1. The average current density of the reinforced conductor as a function of the current density in the superconductor. Parameters are the allowable strain of the conductor, 0.1% and 0.25%, and the modulus of the reinforcement, after reference 2.

with ceramic insulation is very promising,[5] and could be applied to MP35N. It remains, however, the general need for conductors with higher strain tolerance, and especially for high-strength, high-modulus reinforcement material, which can be co-wound or integrated in the conductor.

Resistive Magnets

There are three important parameters, that determine the strength of the magnetic field that can be achieved: the available power, the degree of optimization of the magnet design, and the materials used. The interaction between these three parameters is such that extra power can compensate for a bad design or insufficient materials. Considerable efforts have gone into the understanding of the physics of magnets, with the result that the NHMFL has not only the most efficient but also the most cost-effective, high-power magnets in the world. This was made possible through the invention of the Florida-Bitter magnet.[6] Future improvements will have to focus on increasing the reliability even further and introducing the right measures to cope with the endforces.[7]

A basic relationship describing the power W required to generate a magnetic field B is $B=G(\lambda W/\rho a_1)^{1/2}$ with λ the space or filling factor (conductor volume/total coil volume), ρ the specific conductor resistivity, a_1 the inner magnet radius, and G the Fabry factor that includes coil shapes, dimensions, and current density distributions within the magnet. Because of the Lorentz forces, materials with higher strength have to be used if stronger fields are to be generated. If we have to choose a material with, let's say, 20% higher resistivity, an equal amount of additional power is needed if the same field is to be generated. Only high-strength conductors with higher conductivity than presently available can reduce this penalty, and should be part of a materials development program. Microcomposite conductors are most promising, since they have a significantly higher strength than the rule of mixtures predicts. It has been proposed to develop poly-helix magnets by machining thick cylinders with EDM and applying the Florida-Bitter pattern.[8] To make this idea successful, it would require replacing the traditional method of swaging by new ways of cold working. Equal cross-section angular extrusion of CuAg microcomposites has been investigated earlier at the NHMFL.[9] It remains the challenge to find a method for large cross-sections as required for poly-helix magnets, i.e., about 100 mm diameter. Another possibility exists in sandwiching the Bitter plates with thin plates of very-high-strength disks. This method would have the advantage that one could tailor turn by turn the conductor to the local stress level, and would be especially helpful in the end turns where high stiffness is required to cope with the endforces. Finally, one could also investigate in a jointing technique of the Florida-Bitter disks. In any case, the efficiency and field levels of resistive magnets can only be further improved when high-strength conductors with high conductivity in sheet form will be available.

Pulse Magnets

Four main parameters determine the field that can be achieved: the available energy, stored in a capacitor bank or a generator, the degree of optimization of the magnet design, the available materials, and the energy that can be dissipated in the magnet, i.e., its heat capacity. Similar to resistive magnets, limitations in materials or in the magnet design can be compensated by use of additional energy, however, with the penalty of increased magnet volume. Based on the analysis of resistive magnets, especially the poly-helix magnet, a detailed understanding of the physics of pulsed magnets has been developed, resulting in powerful computer codes to optimize the complex interactions of the many parameters.[10] Radial stress transmission between the inner layers is suppressed for reduced hoop stress, and each layer has its own reinforcement. The Lorentz force is shared between the conductor and the reinforcement in an optimized way, i.e., the Young's moduli, strain tolerance, and strength of both are matched while maintaining the plastic deformation of the conductor within its allowable limits. Similar to HTS, higher fields could be reached if strength and Young's modulus of the reinforcement would be better, and if strain tolerance and fatigue behavior of the conductor could be improved. Corresponding requirements for the materials development are essential. In addition, conductors with high conductivity and high heat capacity are needed for less heating. Generator-driven magnets require, because of their low operating voltage, conductors with large cross-sections, which are challenging to manufacture.

Materials Research

In the following, we list a variety of approaches to meet the above listed requirements for improved or new materials. The proposed methods represent a selection, which we consider promising.

Conductors

In *metal-metal microcomposites*, such as Cu-Ag and Cu-Nb, a strength level of up to 1.5 and 2 GPa, respectively, has been achieved in wires of small cross-section and is attributed to the refined structures, which can be achieved through specific manufacturing techniques. Figure 2 gives an example. Further optimization of the properties of these composites is possible. Particularly, to achieve the required high-strain tolerance, one can utilize heat treatment and changes in composition to modify the microstructure. For instance, by increasing the Ag content in Cu-Ag materials, low modulus conductors with the same strength could be produced, which translates into higher strain tolerance. Ultra-high ductility was reported in Cu by special heat treatment promoting microstructured components embedded in nanostructured components,[11] and we propose to apply the same method to CuAg microcomposites. Further systematic research should concentrate on interface structures, internal stresses, strain hardening, and thermodynamic properties of Cu-Ag and Cu-Nb composites. The interface structure, on both microstructural and atomic scale, governs the strengthening mechanism and physical properties (such as conductivity) of the composite. The internal stresses affect the elastic-plastic response of the conductors to Lorentz forces and thermal stresses.[12] After cold work, the two phases are exposed to induced stresses of opposite sign. We have shown that cyclic loading, for instance by operation in a pulse magnet, creates additional dislocations, which relieve the internal stresses resulting in a higher elastic stress range. This is related to the strain-hardening rate where basic research has the promise to develop conductors with higher strength and/or higher strain tolerance.

The development of *high-strength pure copper* through generation of nanograins and twins in addition to high-density dislocations seems to be very promising. The materials can be fabricated by cryogenic deformation plus thermal heat treatment, which have shown to promote twin formations. Since twins strengthen the material significantly and have limited scattering effects on the electrons, it will provide high strength and high conductivity to the conductors. Other approaches we can consider are to promote the twin

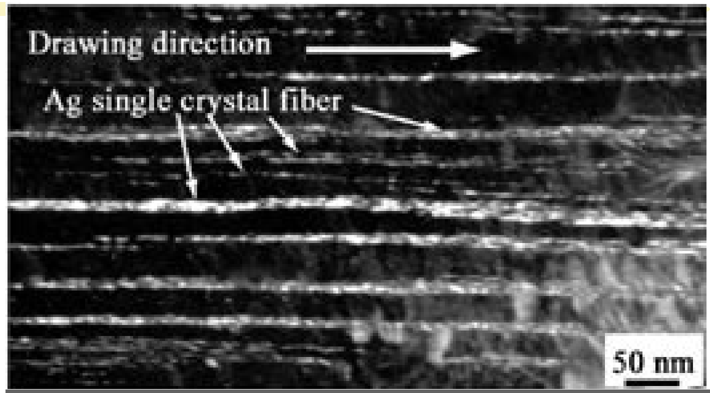

Figure 2. Dark field transmission electron microscopy image showing single nano-Ag fibers embedded in Cu matrix in a Cu-Ag microcomposite high-strength conductor. The contrast within a crystal of nano-Ag fiber indicates the high internal stresses in the fiber.

formation using electro-deposition or similar methods, such as physical vapor deposition. It has been reported that these techniques can produce a high density of twins in Cu, which strengthens it significantly. The work performed at the NHMFL, and funded through an In-House Research Program award, has shown that cold work at cryogenic temperatures is a very promising method to form high-density dislocations and nanotwins.[13] We have obtained a UTS of 580 MPa for pure Cu at room temperature and 680 MPa at 77 K with a conductivity of 96% of the international annealed copper standard. These values were obtained with an area reduction of only 90%. A necessary second step is now to improve the annealing behavior by investigating low-alloyed Cu or low weight-percent CuX microcomposites, where X is a second component with little impact on the Cu conductivity.

Macrocomposites, and especially hybrid-composites consisting of high conductivity materials, such as Cu, Cu alloys or microcomposites, and high strength reinforcement materials should be assessed. Future research should consider the use of different reinforcement components, such as maraging steels, that are strengthened mainly by the precipitation of an intermetallic compound rather than deformation. One should investigate different conductor geometries and the bonding issue, either by cold rolling or adhesives. First studies have shown that hybrid-composite conductors, made from a mixture of microcomposite conductors, high-strength Cu wires, and high-strength reinforcement strips would be a very promising way to tailor conductors to specific applications.[14] Instead of using stainless steel for cladding the Cu or Cu composite core, we will consider the repetitive roll bonding to combine Cu with reinforcement material. In order to achieve strength of greater than 1 GPa with 30% volume fraction of the reinforcement material, as it is required for reasonable conductivity, the strength of the reinforcement materials must be around 3 GPa.

Reinforcement Materials

Various *ultra-high strength and high-modulus superalloys,* such as cobalt alloys have high modulus and high strength. At the NHMFL, we have obtained a UTS of 2.6 GPa at 77 K in MP35N, which has a modulus of 240 GPa at 77 K. Our investigations show that texture and nanoplatelets development during the cold work contribute to the strength and anisotropy of the cobalt alloys. With the goal of obtaining reinforcement material of up to 3 GPa, we propose to optimize the texture and refine further the structure. Of extreme importance is to investigate the addition of high-modulus elements to the existing alloys in order to achieve even higher-modulus alloys. We also propose to study and optimize the thermal expansion coefficient to match favorably conductor and reinforcement for magnets operated at cryogenic temperatures.

Metallic glass, formed by supercooling the liquid state of metallic alloys, was reported to have very high fracture strength (5.2 GPa) and modulus (270 GPa).[15] The mixture of glass and nanocrystalline can produce high-strength materials with acceptable ductility. Up to now, little work has been done for cryogenic applications of this material, but may be promising.

High-strength epoxy-matrix composites have a great potential for further improvements. Recently, bone-shape Ni fibers were found to strengthen cement significantly. It is suggested to develop high-strength M5 or Zylon fibers with bone shape to strengthen the matrix. We also suggest developing composites with different architectures from these strong fibers so that the composite has the strength in the direction optimized for magnet design. The bonding between the fibers and the epoxy would have to be investigated, both experimentally and with simulation approaches, such as molecular dynamics.

Conclusions

The detailed understandings of the physics of magnets, and consequently magnet analysis, have obtained a high degree of perfection over the years, resulting in powerful optimization codes and international leadership in high-field magnet technology. The world records underline these successful efforts. Further progress now depends crucially on the availability of better materials for magnets.

Based on our exploratory work during the last years on conductors, we propose to focus on micro- and macrocomposite conductors, and high-strength Cu. The potential of cryogenic deformation and tailored macrocomposites is only in its beginnings and should be further explored.

Concerning reinforcement materials, we encourage investment in the development of high-modulus metal alloys and organic fibers at the theoretical limit of ultimate strength. Such materials would excite enormous industrial interest.

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